Results of Copper-Silver Rail Materials Tests

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Abstract—The goal of this phase of our investigation of better rail materials was to assess the multiple shot performances of copper-silver alloy (Cu-24% Ag) test coupons. The focus of these tests was on the assessment of changes in material properties and microstructure of test coupons. The primary metric used was the change in hardness. Material surface deformations and microstructure changes were evaluated by optical microscopy and scanning electron microscopy. Hardness gradually increased as the number of tests increased. Test coupons in four states were studied: pretest; after one pulse test; after three pulse tests; and after eight pulse tests. The changes in hardness are related to the initial state of strain and dislocation distributions in the test specimens. The hardness is changed by the nucleation of new strain-free crystallites within the heavily worked, dislocation-dense grain structure. An annealing, recrystallization, and re-straining model is proposed to predict the bandwidth within which the hardness will fluctuate. The retained hardness of the copper-silver alloy test coupons has an average value that corresponds to a tensile strength greater than 650 MPa (100 ksi). This is well above the 500 MPa strength of the usual contacting aluminum alloy armature. Based on these test data, it is concluded that copper-silver remains an attractive material for use as a strong and thermally stable conductor.

I. INTRODUCTION

Copper-silver alloys have an outstanding combination of high strength and high conductivity that make them appealing for applications of high-current conductors. Efficient mechanical and thermal designs are needed for high-performance rail conductors in electromagnetic (EM) launchers. The choice of conductor materials and bore insulator materials affects the efficiency and durability of the launcher as an electrical-to-kinetic energy converter. The rail conductor must possess high mechanical strength, high conductivity, low wear rates, and long fatigue life. During a launch cycle, the rail conductors are typically at a temperature of about 300K at initiation of the current pulse. During the launch pulse, the rails are resistively heated to elevated temperatures of about 1000K at heating rates of 10^6 to 10^8 K/s for a typical duration of less than 10^{-2} s.

The basic conductor requirements are similar to those for high-field magnets. For example, the combination of high strength (>1 GPa) and high conductivity [>75% IACS

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(100% IACS = electrical conductivity of 58.0 MS/m^{-1})] is targeted for a 100 T magnet component powered by a 600 MJ, 560 MW generator [1]. Copper-silver has received the most attention for this type of high-field magnet application.

Copper-silver alloys are promising for high-strength, high-conductivity applications for two reasons. The first is that strength can be manipulated by conventional thermomechanical processing to achieve tensile strength values greater than 1000 MPa (> 140 ksi). The second is that silver is unique in its benign effect on the conductivity of copper. Silver has little effect on conductivity, which is reduced by most alloying elements that go into solution in copper alloys. Impurities and other alloying elements—except silver—decrease the electrical conductivity of copper alloys [2].

Our previous experimental studies of copper-based rail conductor materials have reported on the performance of five different commercial copper alloys [3], a carbon fiber-reinforced copper composite [4], an initial survey of obtainable properties in a cast and rolled copper-silver alloy [5], and an assessment of the performance of a copper-silver alloy under electromagnetic launch conditions. In the previous study, a more heavily worked material was used. The microstructures were stable when exposed to elevated temperature. The ultimate tensile strength (UTS) increased after a single launch test. The rail coupon test produced subtle changes in the test coupon microstructure, but these changes appeared not to affect strength or electrical conductivity.

In this study, the same heavily worked material is subjected to multiple pulse tests to assess whether these high strengths and conductivities are retained following multiple thermomechanical cycles. This information is the next step in the evaluation of the thermal fatigue resistance of copper-silver as potential rail conductor alloys.

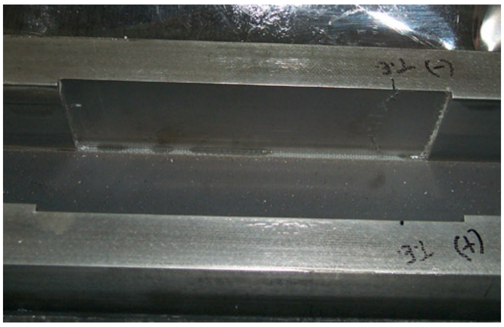
II. Experimental Approach

The experimental approach used in this study matches that of the previous studies of conductor test coupons [3–5].

A. Copper Alloy Coupon Selection and Preparation

Test coupons of the heavily worked copper-24% silver alloy (Cu-24% Ag) were selected to evaluate the response to the repeated high-current operating conditions, by multiple pulse tests, that are observed close to the breech of an EM launcher.

The test coupons fabricated from the rolled strips of Cu-24%Ag alloy were 125 mm long and 44 mm wide. The test coupons were made from strip that was flat-rolled to 2.5 mm (0.100”), the thickness required for insertion into the machined slot of the test conductor, as shown in Fig 1. The alloy was analyzed in four conditions: pretest, after one pulse test, after three pulse tests, and after eight pulse tests.



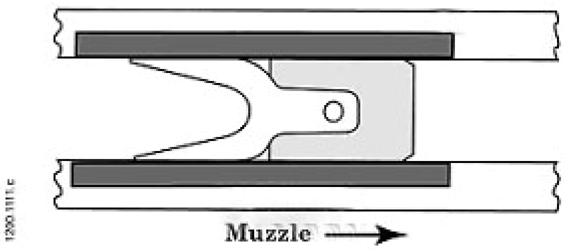
(a) Cavity for Cu-24%Ag test coupon.

(b) Test coupon in place before the test.

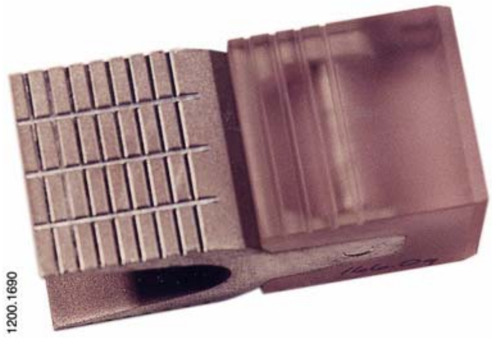
Fig. 1. Experiment Setup.

B. Electromagnetic Launcher Test Apparatus

A 40 mm, square-bore, medium-caliber launcher was used for all the tests. The test armature was the standard design made from aluminum with a polycarbonate bore rider. The test armature was identical to that used in previous studies [3–5]. Before launch, the armature was placed in contact with the test coupon at the start-up position. Launch test data were collected in the forms of breech and muzzle voltage traces and current pulse profiles. Test conditions were chosen to match those of a previous study so that the copper-silver coupon performance could be compared to previous studies [3]. Fig. 2(a) shows a schematic of the armature in its test position, and Fig. 2(b) shows the armature and bore rider.



(a) Schematic of the armature in its loaded, ready-to-launch position.



(b) The armature and bore rider.

Fig. 2. Test articles.

C. Test Material Evaluation

To analyze the effects of repeated launch loads on the microstructure and properties of each test coupon, transverse sections (perpendicular to the rolling direction) were cut for microstructural observation and hardness testing.

To prepare for metallographic analysis, the samples were cold mounted, machine ground using 240-, 320-, 400-, 600-, and 800-grit silicon carbide paper, and machine polished with 1 µm and 0.6 µm diamond pastes. Specimens were etched for 30 seconds with an etchant consisting of 50% nitric acid and 50% distilled water. The microstructural features were documented using photomicrographs obtained with an optical microscope and a scanning electron microscope (SEM).

Hardness measurements were taken from a polished but un-etched sample with a Vickers hardness tester using a load of 30 kg. Visual observations of the transfer of wear material and its morphology were made on the coupons following the launch tests. The electrical conductivity was measured using a conductivity meter (model M4900C, K. J. Law Engineers, Inc., Novi, MI).

III. RESULTS

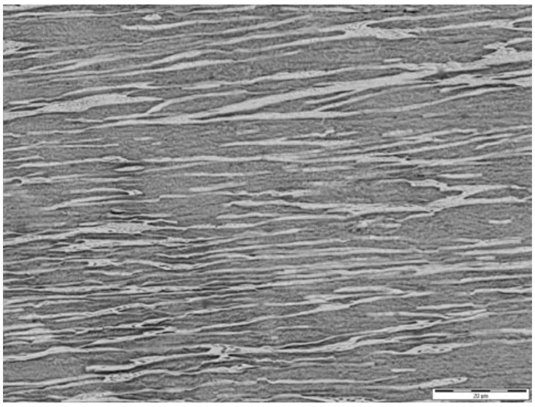
A. Pre- and Post-Test Characteristics of Coupons

The main properties of interest for materials used as EML conductors are strength (hardness) and conductivity (electrical and thermal). Previous studies suggest that the conductivity properties of the alloy Cu-24%Ag are adequate for electromagnetic launch applications. This study evaluates the strength of Cu-24% Ag after multiple pulse tests using change in hardness as the primary metric.

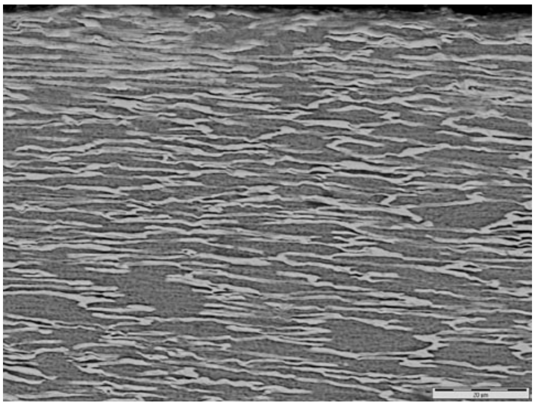
Material surface deformations and microstructure changes were evaluated by optical microscopy and scanning electron microscopy.

B. Microstructure

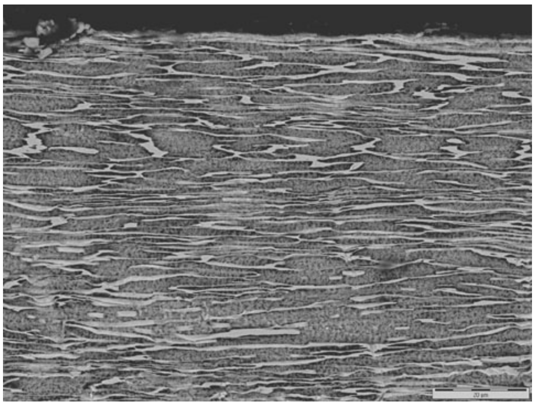
The microstructures of the Cu-24%Ag coupons evaluated in this study are shown in Fig. 3. The SEM images are of the cross-section along the short transverse of the coupons. The images show that the Cu and Ag phases were aligned along the drawing direction. In general, the typical copper-silver alloy microstructural features are observed. The darker phase is the copper-rich solid solution, while the lighter regions are the eutectic structure consisting of both copper-rich and silver-rich solid solutions. The eutectic phase ribbons consist of finer copper and silver filaments [1], [5]. The two phases are inhomogeneously deformed during the rolling process.



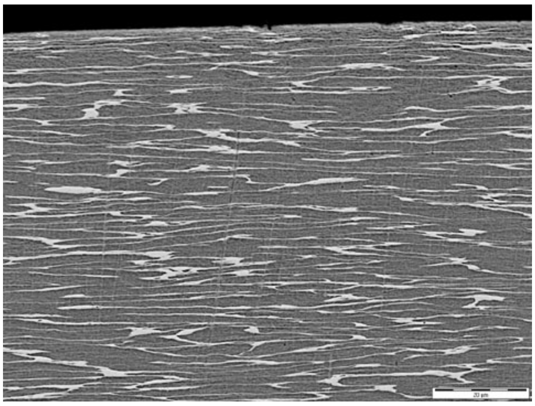
(a) As received.



(b) 1-shot.



(c) 3-shot.



(d) 8-shot.

Fig. 3. Microstructures of as-received and post-test material.

As the strain in the coupons increases due to multiple launches, both the dendrite spacing and the inter-lamellar spacing between Cu and Ag decrease. The decrease in thickness is noticeable in the area immediately under the contact surface. A compact and thin group of dendrites and eutectic areas is observed in Fig. 3c. This sub-surface area is directly exposed to high temperature conditions.

C. Properties of Cu-24%Ag

1. Hardness and Strength

The mechanical and electrical properties of the test coupons are shown in Table 1. For the first three test coupons, the microhardness data show that the hardness of the coupons increased as the number of launch tests increased. A gradual plateau was then reached at some point between the 3-shot and 8-shot sample, since the hardness results were similar. This suggests that this particular alloy, under these particular conditions, is affected by the launch conditions only up to a point of equilibrium.

TABLE 1. PRE- AND POST-TEST HARDNESS, ELECTRICAL CONDUCTIVITY, AND STRENGTH

Coupon Description	Hardness (HV)	Conductivity (%IACS)	UTS (MPa)
As-Received Coupon	178	85	622
1-Shot Coupon	186	85	652
3-Shot Coupon	196	85	686
8-Shot Coupon	195	85	684

A relationship between the UTS y and the hardness x, of the form y(MPa) = $k*x$(HV) was used to calculate the UTS. This relationship is considered to offer a reasonable estimate of a material's UTS for a variety of metals, including high-strength copper alloys [7]. From the data provided in these publications, the average for all the values of k is 3.5.

2. Electrical Conductivity

Table I includes the values of the measured electrical conductivity of the copper-silver test coupons. The electrical conductivity was 85% IACS pre- and post-test. No change in conductivity between the as-received and the post-test material indicate the stability of the electrical conductivity of these Cu-24%Ag alloys.

IV. DISCUSSION

In previous studies, a lingering question about the copper-silver alloy has been whether it will gradually soften and eventually reach a minimum hardness for elastic operation after a certain number of load repetitions [8]. A numerical analysis technique [9], which used the current-density distribution to predict the temperature distribution in a test coupon configuration similar to that in our tests, calculated the maximum temperature with the copper-silver test coupon in place was 414K. From the materials data [10], it is known that the copper-silver alloy retains its strength after exposure to a peak temperature of 414K. The conclusion reached was that as long as the conductor was operated below this softening threshold, the necessary conditions for multi-cycle conductor operation within the elastic regime were available.

As the next step, this work evaluates the performance of a strong conductor material after a certain number of load repetitions. We show in this work that the strength and conductivity of Cu-24%Ag are not affected by repeated pulse loads. In fact, the hardness of the alloy increased with the number of load repetitions. The changes in hardness are related to the initial state of strain and dislocation distributions in the test specimens. The hardness is changed by the nucleation of new strain-free crystallites within the heavily worked, dislocation-dense grain structure. An annealing, recrystallization, and re-straining model can predict the bandwidth within which the hardness will fluctuate. The growth rate of recrystallized grains has two components: the grain boundary energy and the driving pressure. At high temperatures, the driving pressure is dominant over the relatively lower grain boundary energy [11]. The retained hardness of the copper-silver alloy test coupons has an average value that corresponds to a tensile strength greater than 650 MPa (100 ksi). This is well above the 500 MPa strength of the usual contacting aluminum alloy armature. Based on these test data, it is concluded that copper-silver remains an attractive material for use as a strong and thermally stable conductor after repeated pulse loads.

V. CONCLUSION

Coupons of a copper-silver alloy were tested under the high-current, low-velocity conditions close to the breech of a laboratory launcher. Coupons were evaluated in different states: pretest; after one pulse test; after three pulse tests; and after eight pulse tests.

The conclusions are as follows:

1. The microstructures of copper-silver alloys are stable when exposed repeatedly to elevated temperatures.

2. Changes in microstructural features did not affect the strength or conductivity of the coupons.

3. The strength of the copper-silver coupons increased as the number of pulse tests increased. The values of UTS range between 622 MPa and 686 MPa, and the corresponding measured electrical conductivities were 85% IACS for the various test states.

4. The data suggest that the effect of the launch conditions on strength reaches an equilibrium level and may fluctuate in a narrow band thereafter.

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